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Stellar Encounters with Black Holes

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I describe the results that have been obtained within the project *Stellar encounters with Black Holes* on the JUMP supercomputer of the John von Neumann Institute for Computing in Jülich. The main results from three types of encounters are summarized: the coalescence of a Neutron Star Black Hole binary system that merges due to the emission of gravitational waves, the disruption of a solar type star by a stellar-mass Black Hole and finally the tidal compression and possible thermonuclear explosion of a White Dwarf by a Black Hole of a few hundred solar masses.

1 Introduction

Like human beings stars undergo evolutionary stages from birth to death. Depending on their initial mass they will finally end up as either as a White Dwarf, a Neutron Star or a Black Hole.

The most common stars with masses comparable to that of our Sun, but below 8 $M_{\odot}$, will become White Dwarfs (1 $M_{\odot}$ = one solar mass= $1.99 \cdot 10^{33}$ g; in the following I will refer to such stars as Main Sequence stars). Such a White Dwarf is a burnt out stellar corpse, with a size similar to our planet earth, but a mass comparable to that of our Sun. Often White Dwarfs are surrounded by beautifully colored, so-called planetary nebulae. Rarer, more massive stars ($M > 8$ $M_{\odot}$) will end their lives in one of the most spectacular fireworks that our Universe has to offer: a (core-collapse) Supernova explosion. Once such a massive star has used up the nuclear fuel in its center, its balance between the outward directed pressure forces and the inward-pulling gravity is lost and the star starts to collapse under its own gravitational attraction. If the star is not too massive, say below 25 $M_{\odot}$, this collapse can be halted once the matter in the stellar center has been compressed to densities similar to the those inside an atomic nucleus ($\rho_{\rm nuc} \approx 3 \cdot 10^{14}$ g cm^{-3}). Above this density matter becomes extremely incompressible and this brings the collapse to a halt, reverses it and launches an outward moving shock wave that initiates the Supernova explosion. Such an explosion will leave behind an extremely dense stellar remnant: a Neutron Star. With a mass of 1.4 $M_{\odot}$, but a radius of about 15 km, this ultra-compact star itself has densities around nuclear density and can therefore be regarded as a "giant atomic nucleus". For even heavier stars ($M > 25$ $M_{\odot}$) not even the matter pressure at nuclear densities can stop the collapse, the ultimate fate of such stars is the formation of a Black Hole.

As every star will finally form such a compact remnant, the Universe contains myriards of them. The problem is their detection as, under normal circumstances, they do not reveal much about themselves. In some regions of the Universe, for example close to the centers of galaxies or in dense gravitationally bound stellar systems, so-called Globular Clusters, the stellar densities are large enough to frequently allow for collisions. In a given place, say a specific globular cluster, such encounters may be rare by standards of a human lifetime, but as some of the encounters release huge amounts of energy, they may be visible way beyond their own host galaxy. Therefore, despite being a rare event *per galaxy* they may still possess a large *observable* rate.

I will discuss here several types of such collisions that have -in part or completely- been calculated using the JUMP supercomputer facilities: the coalescence of a stellar-mass Black Hole Neutron Star binary system (see Sect. 3), the disruption of a solar-type star by a Black Hole (see Sect. 4) and finally the close encounter of a White Dwarf with a Black Hole of several hundred solar masses (see Sect. 5).

2 Model Ingredients and Numerical Methods

The different types of encounters require very different input physics. Encounters between *Black Holes and a Main Sequence star* are well described by just following the gas dynamics around the hole. The equation of state is well approximated by using a simple polytropic law. As all interesting length scales of the cases we investigated are much larger than the Schwarzschild radius of the Black Hole, the gravity from the hole can be treated to a very good approximation in a Newtonian way.

In the *Neutron Star Black Hole* case a crucial model ingredient is the equation of state (EOS). It must be able to handle the hadronic physics from several times nuclear density (several times 10^{14} g cm^{-3}) down to densities of a few g cm^{-3}. The expected temperatures are in a range of up to a few times 10^{11} Kelvin, so about 10 000 times larger than in the center of the Sun. Therefore, despite the very high densities (where often temperature effects can be neglected) the EOS has to take effects from a non-zero temperature into account. To include neutrino emission also quantities like chemical potentials etc. have to be provided by the EOS. A detailed treatment of the different neutrino flavors is also implemented in our models. In terrestrial material the mean free path of a neutrino of a few MeV is of the order of astronomical units (= distance from earth to the Sun), i.e. such material is completely transparent to neutrinos. In the center of a Neutron Star, however, the neutrino mean free path can be as short as 10 cm, but parts of the debris of a disrupted Neutron Star can again be completely neutrino-transparent. Therefore the neutrino treatment has to account for such opacity effects. In the Neutron Star Black Hole case, relativistic effects are important and they are incorporated into the simulation via a Paczynski-Wiita potential[7]. For details of the physics and the implementation the interested reader is referred to Rosswog et al.[9–17].

For our *Black Hole White Dwarf* cases we are interested in the question whether/under which conditions the White Dwarf can explode by thermonuclear fusion. This means in particular that the energy release due to nuclear reactions has to be fed back into the hydrodynamics. This is computationally extremely challenging as each fluid element (in our case an SPH-particle, see below) has to know its nuclear composition and has to evolve this composition in time. Once nuclear burning becomes important, the nuclear reaction time scales can be shorter than the hydrodynamic time scales by many orders of magnitude. Therefore it is indispensable to apply operator splitting methods. Our approach to this computational challenge is described in detail in Rosswog and Ramirez-Ruiz (2006) and Ramirez-Ruiz and Rosswog (2006)[18,19].

In all of the described cases the Smoothed Particle Hydrodynamics (SPH) method is used to solve the equations of hydrodynamics. It is a Lagrangian particle scheme, i.e. all the information about the flow is carried by particles that are evolved in time. The corresponding equations can be derived form a Lagrangian, therefore the exact conservation of mass, energy, linear and angular momentum are guaranteed even for the discretized fluid equations. As in many of the problems angular momentum and its transport via gravitational torques determines the dynamical evolution, its conservation is an indispensable asset. The computationally most expensive part, common to all of these simulations, is the treatment of self-gravity of the fluid. It is calculated via a parallelized binary tree (see e.g. Benz 1990[3]) that scales like $N \log N$ (N being the SPH particle number) rather than the N^2-dependence of the brute force, pairwise evaluation of gravity.

3 Coalescence of Neutron Stars with Black Holes

Binary systems consisting of two compact objects, either two Neutron Stars or a Neutron Star and a stellar-mass Black Hole, are among the most promising sources for gravitational waves that could be detected in the near future by ground-based detector facilities. The gravitational waves carry away energy and angular momentum from the binary system, therefore the two components of the system will slowly drift towards coalescence.

This final coalescence releases a tremendous amount of energy: more than 10^{53} ergs, more than the energy our Sun could emit during the whole age of the Universe, are released in fractions of a second. Such coalescences seem to be responsible[4,8,5,6,1,14] for a good fraction of the most violent explosions in the Universe since the Big Bang: Gamma-ray bursts, tremendoulsy violent explosions that emit copious amounts of gamma-rays.

We have simulated the last milliseconds in the life of a Neutron Star Black Hole binary system. For technical reasons we have started this investigation focusing on the high-mass end of the expected Black Hole mass distribution, i.e. we focused on Black Holes with masses larger than 14 $M_\odot$. Black Holes possess a so-called *innermost stable circular orbit* at a radius $R_{\rm ISCO}$, inside of which no particle can revolve around the hole in a stable, circular fashion. Our recent simulations[17] show that the Neutron Star, once it has come close enough to the Black Hole, transfers a large portion of its mass directly into the hole. Only after that stage an accretion disk can form. Such disks are observed everywhere in the Universe where gas with enough angular momentum is pulled towards an accreting object: they occur around new-born stars, in freshly formed planetary systems, around the supermassive Black Holes in the centers of Galaxies and they are believed to be a vital ingredient for the central engine of a Gamma-ray burst. However, none of our investigated cases formed the hot (several 10^{10} Kelvin) and massive ($\approx$ 0.1 $M_\odot$) accretion disk that is needed to launch a Gamma-ray burst. Instead, the disk that finally forms has only a relatively small mass. Most of it resides inside the innermost stable circular orbit and is therefore falling rapidly towards the hole without having enough time to heat up. A small amount of the initial Neutron Star mass takes up a lot of the orbital angular momentum and transports it outward in rapidly expanding tidal tail. A snapshot of such a disruption process is displayed in Figure 1, movies can be found at `http://www.faculty.iu-bremen.de/srosswog/movies.html`.

This does not necessarily mean that Neutron Star Black Hole mergers generally have to be ruled out as Gamma-ray burst central engines. However, the high mass end of the distribution that we began our study with does not seem to be promising. So if these systems do not produce a Gamma-ray burst how else would they make themselves known? They

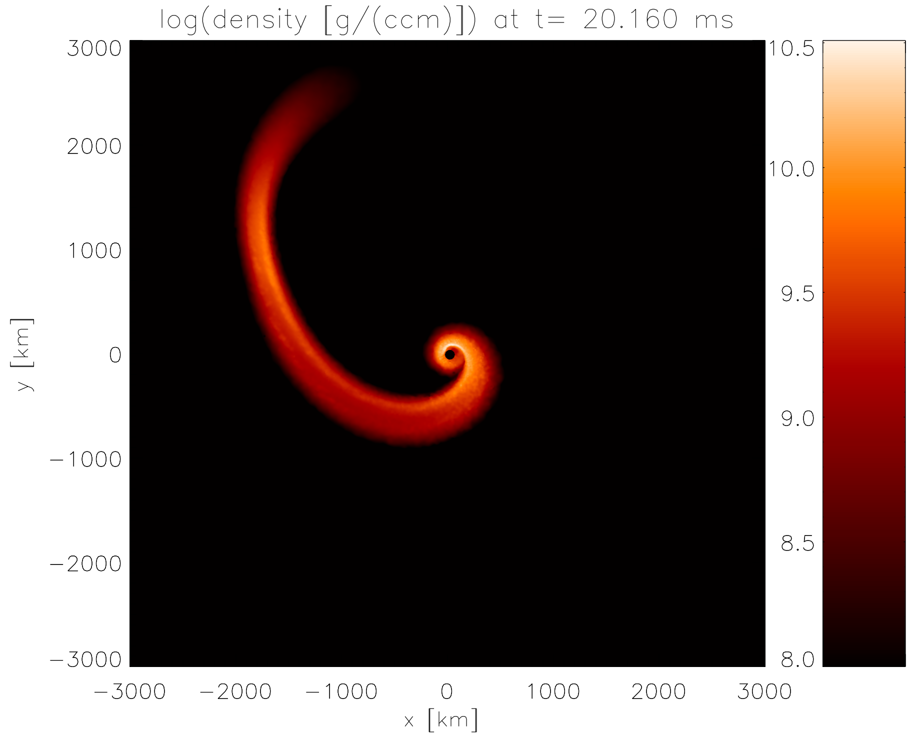

Figure 1. Snapshot of the tidal disruption process of a 1.4 solar mass Neutron Star by a Black Hole of 14 solar masses. Color-coded is the column density through the Neutron Star debris.

will definitely be a strong source of gravitational waves. The tidal tails also hold some promise for observation. Depending (quite sensitively) on the mass of the Black Hole, up to 0.2 $M_\odot$ of the Neutron Star get thrown out into space with velocities of about half the speed of light. This material initially has very high densities where nature favors very large nuclei containing hundreds of neutrons and protons. As this material expands very rapidly, the physical conditions and therefore the preferred nuclei change continuously. This leads to a constant transmutation/decay of the present nuclei and goes along with constant electromagnetic emission. This could (like a type Ia Supernova) lead to an electromagnetic emission that is powered by radioactive decays. It will produce a flash with a maximum intensity in the optical/near infrared band[17].

4 Disruption of Main Sequence Stars by Black Holes

In dense stellar systems like globular clusters stellar-mass Black Holes, with, say, 10 $M_\odot$, will also collide with the most common type of stars: Main Sequence stars like our Sun. This will in most cases be a fatal event for the star. Such a disruption of solar-type star would occur on substantially longer time scales than the previously described encounter with a Neutron Star, here the disruption process will take many hours.

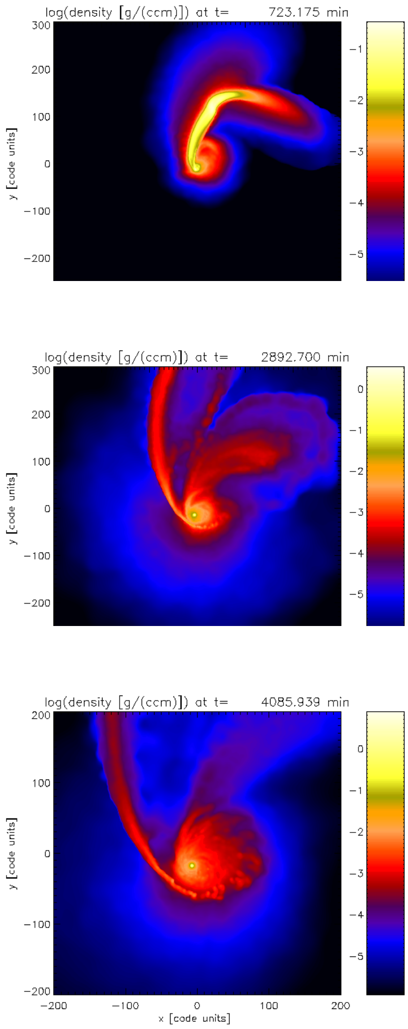

Figure 2. A solar-type star becomes tidally disrupted by a 10 $M_\odot$ Black Hole. After a first close fly by the hole grabs some of the stellar material in the form of an accretion disk while most of the stellar debris gets flung out again (panel one). The self-gravity of the latter material is strong enough to lead to the formation of a stellar core-like object (high density region in panel one) that falls -in a second approach- back towards the Black Hole. This approach completely disrupts the star (panel two) whose remains continue to rain down on the accretion disk around the Black Hole (panel three; 1 code unit= 10^{10} cm).

A movie of such a simulation can be found under `http://www.faculty.iu-bremen.de/srosswog/pop_science.html`. Some snapshots of such a disruption process of a solar-type star by a 10 $M_\odot$ Black Hole are displayed in Figure 2. After the first close encounter the Black Hole grabs some material that gathers in an accretion disk around the hole while most of the debris is flung away from the Black Hole (first panel). The self-gravity of this latter material is strong enough to form a stellar core of about 0.3 $M_\odot$ which then falls back towards the Black Hole. In a nearly central collision with the hole this core is completely disrupted and its remains rain down onto the previously formed accretion disk (second and third panel of Fig. 2).

Depending on the closeness of the impact, the accretion process may have to compete against nuclear burning processes that are triggered by the disruption. In some cases the hydrogen of the star will ignite explosively (i.e. on a time scale shorter than the one on which the star can react) as a particular, hydrogen-explosion Supernova.

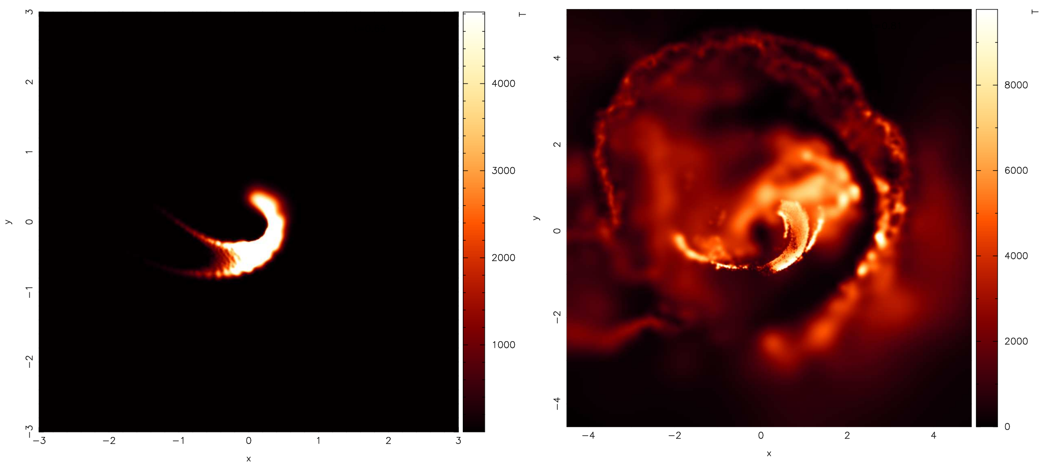

Figure 3. Tidal ignition and detonation of a White Dwarf. As the Carbon-Oxygen White Dwarfs passes the point of maximum compression it heats up to about $5 \cdot 10^9$ K and ignites its nuclear fuel (left panel; temperatures are in units of 10^6 K). During the passage more than its entire gravitational binding energy is released via nuclear burning processes, therefore the White Dwarf blows up in a violent explosion.

5 White Dwarf Explosions Induced by Black Hole Fly Bys

As most stars in the Universe have masses comparable to that of our Sun, the most common remains after a stellar lifetime will be White Dwarfs. In a Globular cluster about 10 % of the disrupted stars will be White Dwarfs[2]. A star passing a Black Hole will be disrupted if the tidal forces (similar to the forces that produce the tides on earth) overwhelm the self-gravity of the star. As we want to know whether a White Dwarf can be compressed enough to trigger a thermonuclear explosion, we are interested in the strongest possible encounters with the distance of closest approach being much smaller than the tidal radius where the star becomes disrupted. Such requirements cannot be met by all types of Black Holes as for the most massive ones, such as the one in the center of our Galaxy, the White Dwarf would be swallowed by the Black Hole before it can be disrupted. Therefore for this study only Black Holes with masses smaller than 10^4 $M_\odot$ are interesting.

In a good fraction of the investigated cases the White Dwarfs become strongly enough compressed so that the temperatures rise beyond 10^9 K, i.e. to more than a hundred times the temperatures in the center of the Sun. At the end of their normal stellar lifetimes White Dwarfs had stopped nuclear burning as there was no means to reach high enough temperatures to ignite the ashes form previous burning stages (mostly Helium, Carbon or Oxygen). In such a fly by, however, a White Dwarf can reach much higher temperatures than ever before in its life. They are large enough to ignite the ashes the White Dwarf is made of and the nuclear reactions that now set in can become extremely fast: more than 10^{51} ergs, more than the energy our Sun would radiate in a billion years, will be released within fractions of a second. A White Dwarf cannot react on this short time scale by expanding and thus slowing down the nuclear reactions, it has to take up all this thermonuclear energy and then blow up in a violent detonation.

An example of a thermonuclear explosion induced by tidal compression is shown in Fig. 3. A 1.2 $M_\odot$ White Dwarf composed of Carbon and Oxygen passes close to a 500 solar mass Black Hole. At the point of maximum compression more than $5 \cdot 10^9$ K are reached which ignites the White Dwarf. The deposition of more than 10^{51} ergs results in a violent thermonuclear explosion.

6 Concluding Remarks

I have summarized the current status of our project *Stellar encounters with Black Holes* (S.R., International University Bremen, Germany and E. Ramirez-Ruiz, Institute for Advanced Study, Princeton, USA). This project contains several sub-projects that are very different in terms of the involved physics and astrophysical questions that we hope to answer. The implications of these sub-projects range from gravitational waves over the production of heavy elements to stellar explosion mechanisms and Gamma-ray bursts.

We achieved substantial progress over the time span of this project. Several questions have found satisfactory answers, but also many more interesting ideas and exciting new questions have turned up in the course of this work. They will certainly keep us -and JUMP- busy for the next few years.

Acknowledgments

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References

1. Barthelmy, S. et al., accepted for Nature (2005).
2. Baumgardt, H. et al., ApJ 613, 1143 (2004).
3. Benz,W. et al., ApJ 348, 647 (1990).
4. Berger, E. et al., accepted to Nature (2005).
5. Bloom, J. et al., ApJ in press (2005).
6. Hjorth, J. et al., ApJL, Nature 437, 859 (2005).
7. Paczynski, B. and Wiita, P.J., A&A 88, 23 (1980).

8. Prochaska, J.X. et al., submitted to ApJ Letters, astro-ph/0510022 (2005).
9. Rosswog, S. et al., A&A 341, 499 (1999).
10. Rosswog, S. et al., A&A 360, 171 (2000).
11. Rosswog, S. and Davies, M.B., MNRAS 334, 481 (2002).
12. Rosswog, S. and Ramirez-Ruiz, MNRAS 336, L7 (2002).
13. Rosswog, S. and Liebendörfer, M.B. MNRAS 342, 673 (2003).
14. Rosswog, S. et al., MNRAS 345, 1077 (2003).
15. Rosswog, S. and Ramirez-Ruiz, MNRAS 343, L36 (2002).
16. Rosswog, S. et al., MNRAS 351, 1121 (2004).
17. Rosswog, S., ApJ, 634, 1202 (2005).
18. Rosswog, S. and Ramirez-Ruiz, E., to be submitted.
19. Ramirez-Ruiz, E. and Rosswog, S., to be submitted.